

SciBooNE's neutral current π^0 production measurements

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Abstract. The SciBooNE Collaboration has measured neutral current neutral pion production by the muon neutrino beam at a polystyrene target (C_8H_8). We obtained $(7.7 \pm 0.5(\text{stat.})_{-0.5}^{+0.4}(\text{sys.})) \times 10^{-2}$ as cross section ratio of the neutral current neutral pion production to total charged current cross section at the mean neutrino energy of 1.16 GeV. This result is consistent with the Monte Carlo prediction based on the Rein-Sehgal model

Keywords: neutral current neutral pion, SciBooNE, neutrino oscillation

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INTRODUCTION

In this paper, neutral current neutral pion production by muon neutrinos ($NC\pi^0$) is defined as a neutral current interaction by muon neutrinos where at least one π^0 is emitted in the final state from the target nucleus.

$NC\pi^0$ is a potential major background to the ν_e appearance search, which is the primary purpose of modern neutrino oscillation experiments such as the T2K experiment [1]. This is because the gamma ray from a π^0 mimic an electron from ν_e interaction in a detector such as SuperKamiokande used for the T2K experiment as in many $NC\pi^0$ events both gamma rays are not resolved and give a single electron-like ring. For this reason, a precise measurement of the $NC\pi^0$ cross section is essential. For the T2K experiment, a 10 % uncertainty on this cross section is desired.

EXPERIMENTAL SETUP

The SciBooNE experiment [2] uses the Booster Neutrino Beam (BNB) at Fermilab. The primary proton kinetic energy is 8 GeV and the neutrino flux is dominated by muon neutrinos (93 % total). The flux-averaged mean neutrino energy is 0.7 GeV. The SciBooNE detector is located 100 m downstream from the neutrino production target. The detector complex consists of three sub-detectors; a fully active fine grained scintillator tracking detector (*SciBar*) [6], an electromagnetic calorimeter (*EC*) [7] and a muon range detector (*MRD*). The *SciBar* detector consists of 14336 extruded plastic scintillator strips. The scintillators are arranged vertically and horizontally to construct a $3 \times 3 \times 1.7\text{m}^3$ volume with a total mass of 15 tons. The *EC* is installed downstream of *SciBar* to measure π^0 and the intrinsic ν_e contaminations. The *EC* is a “spaghetti” type calorimeter made of 262 modules comprised of 1 mm diameter scintillating fibers embedded in lead foil. The modules construct one vertical and one horizontal plane, and each plane has 32 modules. The *EC* has a thickness of 11 radiation lengths along the beam direction. The *MRD* is located downstream of *EC* in order to measure the momentum of muons up to 1.2 GeV/c with range. The experiment took both neutrino and antineutrino data from June 2007 until August 2008. In total 2.64×10^{20} POT (protons on target) were delivered to the beryllium target during the SciBooNE data run. After beam and detector quality cuts, 2.58×10^{20} POT are usable for physics analysis; 0.99×10^{20} POT for neutrino data and 1.53×10^{20} POT for antineutrino data. Preliminary results from the full neutrino data sample are presented in this paper.

ANALYSIS

Event Reconstruction

The first step of the event reconstruction is to search for two-dimensional tracks in each view of *SciBar* using a cellular automaton algorithm [8]. Three dimensional tracks are reconstructed by matching the timing and edges of the two dimensional tracks. three-dimensional reconstructed track *3D track* here after.

In order to improve the reconstruction of gamma rays, we introduced *extended track*. Extended tracks are reconstructed based on 3D tracks. There are two steps to reconstruct extended tracks. The first step is merging two 3D tracks on a common straight line. Because some part of single gamma rays are broken into two clusters in SciBar and result in two 3D tracks. Such two 3D tracks are handled as single extended track after merging. The second step is collecting hits around merged 3D tracks. This is because electromagnetic showers sometimes make hits far from the main part of showers and these hits are not associated to 3D tracks.

Some of gamma rays observed in SciBar have energy deposit in EC due to leakage. After event reconstruction in SciBar we search for *EC clusters* (the collection of continuous hits in EC) pointed by 3D tracks in SciBar. We call such a EC cluster as a *matched EC cluster*.

Event Selection

The clearest feature of the NC π^0 production is two gamma rays from π^0 s. While the main background events are divided into two categories; the *internal* background and the *external* background. In the *internal* background events, the neutrino interactions in SciBar produce secondary particles but the interaction modes of them are different from the NC π^0 interaction. The interaction mode in the *internal* background are mainly charged current interaction. The *external* background is particles coming from the outside of the detectors. There are two type of the external background; accidental cosmic rays and *dirt* events. The contribution of accidental cosmic rays in any event samples is small and estimated by data taken during off-beam timing. Hence, our data shown here is after subtraction of the contribution of accidental cosmic ray. In *dirt events*, neutrinos interact with materials such as wall of experimental hall and produce secondary particle which make hits in SciBar. The event selections for NC neutral pion production were developed for selecting two gamma rays but rejecting these backgrounds.

Pre-selection

We use events with more than one 3D tracks to choose two gamma rays events. In addition, we reject events if there are hits at the first layer of SciBar and the timing difference between these hits and the 3D tracks is less than 100 nsec. This reject dirt events where charged particles from outside of the detectors come to SciBar.

Rejection of the side escaping 3D tracks

We reject events with 3D tracks escaping from the side of SciBar. Because most of such 3D tracks are muons produced in the charged current events. After this selection there are still muons stopping in SciBar or escaping from the downstream of SciBar. These muons are rejected in other selections described later.

Decay electron rejection

To reject muons stopping in SciBar, we use the electrons from muon decay. Since most of the decay electrons are not reconstructed as 3D tracks due to their low energy, we search the delayed hits at the edges of 3D tracks. We search the maximum timing difference between the initial edge and end edge of 3D tracks. If a muon decays to electron in a event, the maximum timing difference is corresponding to the muon life time ($\tau_\mu = 2.2 \mu \text{ sec}$). Since most of events without decay electrons have the maximum timing difference less than 100 ns, events with the maximum timing difference less than 100 ns are selected.

Track disconnection cut

Charged current events often have multiple 3D tracks with a common vertex while two gamma rays from π^0 s usually are isolated from each other. Hence, the distance between two tracks is used to separate two gamma rays from charged current event. We search the minimum distance between the edges of all 3D tracks. If there are two particles with

a common vertex, the minimum distance is close to zero. Events with the minimum distance greater than 6 cm are selected.

Proton rejection

Since protons give a large energy deposit in SciBar, the proton track is identified from other particles. Using this information, we require events to have at least two 3D tracks both of which are not protons. By this requirement, we reject charged current events furthermore (for example, events with muon and protons at the final state). We define *Muon confidence level* (MuCL) by using dE/dx information as shown in [2] the MuCL is close to the maximum value (1) for muons and the minimum value (0) for protons. We define a track with MuCL greater than 0.03 as a *non-proton-like* track. Events with at least two non-proton-like tracks are selected.

Electron Catcher Cut

Matched EC Clusters are used to reject muons escaping from the downstream part of SciBar. The two values are used. The one is the energy deposit in the upstream (vertical) EC cluster called $Edep_{upstream}$ and the other is the energy ratio of the downstream (horizontal) EC cluster to the upstream EC cluster called R_{energy} . If there are no matched EC clusters, $Edep_{upstream}$ is set to zero and R_{energy} are left undefined. Since muons tend to penetrate material than γ s, the energy deposit of muon at both upstream and downstream plane are close to each other ($Edep_{upstream} \sim 50$ MeV, $R_{energy} \sim 1$). While gamma rays stop in the short range after conversion with large energy deposit in the upstream cluster. An event are selected if the event satisfy one of three following condition, (i) No matched EC clusters, (ii) $Edep_{upstream} > 150$ MeV and (iii) $R_{energy} < 0.2$.

Two extended track

From this selection, we use the extended track information instead of the 3D track information. To reconstruct π^0 s, events with the number of extended tracks more than one are selected. This cut is also for the dirt rejection since there is a lot of the dirt contribution with one extended track. In such dirt events, single gamma ray comes to SciBar and make two 3D tracks, which is merged as one extended track.

The reconstructed vertex of π^0 s

The reconstructed vertex of π^0 s are calculated as a intersection of two extended tracks. Using this information, we select π^0 s produced only in SciBar to reject dirt events where π^0 s are produced at the outside of SciBar. Hence, the events where the reconstructed z-vertex of the π^0 is downstream of the most upstream position of SciBar are selected.

Reconstructed mass of π^0 s

The left plot in Fig. 1 shows the reconstructed mass of the π^0 calculated as $\sqrt{2E_{\gamma 1}^{rec} E_{\gamma 2}^{rec} (1 - \cos \theta^{rec})}$, where $E_{\gamma 1}^{rec}$ ($E_{\gamma 2}^{rec}$) is the energy of extended tracks ($E_{\gamma 1}^{rec} > E_{\gamma 2}^{rec}$) and θ^{rec} is the 3D angle between two extended tracks. We select events with $50 \text{ MeV}/c^2 < M_{\pi^0}^{rec} < 200 \text{ MeV}/c^2$ to reduce the background events. The fact that the peak value is smaller than the actual π^0 mass (135 MeV) is due to energy leakage of γ s.

We also show the reconstructed π^0 momentum after this selection in the right plot in Fig. 1.

The summary of the event selections

Tab. 1 shows the number of events of data and MC simulation at each event selection stage. We select 657 events after all event selections and the number of signal is estimated to be 374 events (after the subtraction of the secondary

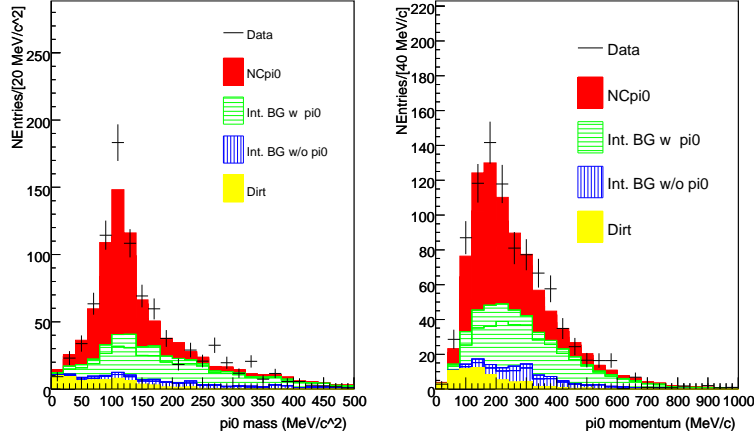


FIGURE 1. The reconstructed π^0 mass before the π^0 mass cut (left) and π^0 momentum after the π^0 mass cut (right). The contributions from the $\text{NC}\pi^0$ signal, the internal background with π^0 s in the final state, the internal background without π^0 s in the final state and the dirt events are shown separately.

TABLE 1. Event selection summary

Event selection	DATA	MC			$\text{NC}\pi^0$ Efficiency
		Signal	Int. BG	Dirt BG	
Pre-selection	11,926	1,919	9,782	895	27.7%
No side escaping	7,444	1,486	5,686	638	21.4%
Decay-e rejection	5,609	1,396	3,766	606	20.1%
Trk. disconnection	3,614	1,332	1,688	595	19.2%
Proton rejection	2,123	745	943	408	10.7%
EC cut	1,534	675	507	399	9.7%
Two extended trks	973	450	383	121	6.5%
π^0 vertex cut	905	434	375	65	6.2%
π^0 mass cut	657	374	197	38	5.4%

π^0 events). The purity and efficiency of $\text{NC}\pi^0$ production after all event selections are estimated to be 61% and 5.4%, respectively.

RESULTS

$\sigma(\text{NC}\pi^0)/\sigma(\text{CC})$ cross section ratio

We measure the cross section ratio of the neutral current π^0 production to the total charged current interaction.

Neutral current π^0 production

The efficiency corrected number of neutral current π^0 events is calculated as

$$N(\text{NC}\pi^0) = \frac{N_{\text{obs}} - N_{\text{BG}}}{\epsilon_{\text{NC}\pi^0}} \quad (1)$$

where N_{obs} is the number of observed events, N_{BG} is the number of background events estimated with the MC simulation, and $\epsilon_{\text{NC}\pi^0}$ is the selection efficiency of neutral current π^0 events calculated by the MC simulation. N_{obs}

and N_{BG} , $\epsilon_{NC\pi^0}$ are 657, 238.3 and 0.053, respectively. The mean neutrino beam energy for true neutral current neutral pion events in the sample is estimated to be 1.16 GeV after accounting for the effects of the selection efficiency.

Total charged current interaction

The total number of charged current interaction is estimated by using the *MRDstopped* sample. We call a 3D track in SciBar matched with a track or hits in the MRD as a *SciBar-MRD matched* track. For the *MRD stopped* events, at least one SciBar-MRD matched track is required to stop in MRD. The details of the selection for the MRD stopped events are described in [2] The number of charged current candidates after correcting for the selection efficiency is calculated as

$$N(CC) = \frac{N_{obs}^{CC} \times p_{CC}}{\epsilon_{CC}} \quad (2)$$

where N_{obs}^{CC} is the number of observed charged current event candidates, ϵ_{CC} and p_{CC} are the selection efficiency and purity for charged current interaction in the sample, respectively. We observed 21702 MRD stopped events (N_{obs}^{CC}). The selection efficiency and purity of charged current events are estimated to be 19% (ϵ_{CC}) and 89% (p_{CC}), respectively.

Cross section ratio

The ratio of the neutral current neutral pion production to the total charged current cross section is measured to be

$$\begin{aligned} \frac{\sigma(NC\pi^0)}{\sigma(CC)} &= \frac{N(NC\pi^0)}{N(CC)} \\ &= (7.7 \pm 0.5(\text{stat.})^{+0.4}_{-0.5}(\text{sys.})) \times 10^{-2} \end{aligned} \quad (3)$$

at the mean neutrino energy of 1.16 GeV, where the systematic error is described later. the Neut expectation is 0.068. Therefore, the measurement is consistent with our MC simulation based on the Rein-Sehgal model [3][4][5] for the pion production.

Systematic errors

The sources of systematic error are divided into four categories, (i) detector response and track reconstruction, (ii) nuclear effects and neutrino interaction models, (iii) neutrino beam and (iv) dirt density. We vary these sources within their uncertainties and take the resulting change in the cross section ratio as the systematic uncertainty of the measurement. Tab.2 summarizes the systematic errors in the neutral current neutral pion cross section ratio. The total systematic error is $^{+0.4}_{-0.5} \times 10^{-2}$ on the cross section ratio.

TABLE 2. Summary of the systematic errors in the neutral current neutral pion cross section ratio

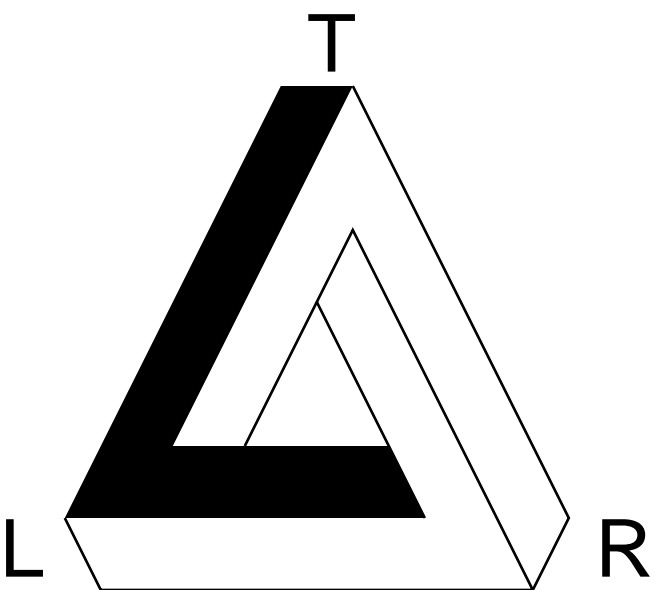
Source	error ($\times 10^{-2}$)	
Detector response	-0.4	0.3
ν interaction	-0.2	0.2
Dirt density	-0.1	0.0
ν beam	-0.1	0.2
Total	-0.5(-0.482)	0.4(0.411)

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